

# Probing the Structure of Halo Nuclei

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**Abstract.** Our understanding of halo nuclei has so far relied on high-energy scattering and reactions, but a number of uncertainties remain. I discuss in general terms the new range of observables which will be measured by experiments around the Coulomb barrier, and how some details of the reaction mechanisms still need to be clarified.

Halo nuclei are nuclei in which there is very weak binding of the last nucleon or pair of nucleons. There is then a large probability for these nucleons tunneling into the classically-forbidden regions outside a more tightly bound core. The overall r.m.s. matter radius of the nucleus is then very large, resulting in the large interaction cross sections which were the first experimental signatures of such nuclei [1], and which continue to yield important information [2].

Since then, two further experimental probes of halo structure have been developed, still using high-energy reactions. The first is to look at the momentum distributions following fragmentation of the halo nucleus at high velocity. In such reactions the sudden or Serber model for breakup implies that the fragments move after the collision with velocities reflecting their range of Fermi momenta in the initial halo nucleus. Experimentally, very narrow momentum widths are found [3, 4]. By the Heisenberg Uncertainty Principle, a narrow momentum uncertainty reflects a large spatial extension.

The second probe is the Coulomb breakup cross section when the nuclei are incident on highly charged targets. These measurements use a heavy target as a source of virtual photons, and reconstruct the dipole strength function by measuring the angles and velocities of all the fragments. Experiments find a strong concentration of dipole breakup strength in low continuum energies. This is because the halo neutrons, although not charged themselves, are sufficiently far from the charged core nucleus, that the centres of mass and charge no longer coincide. The repulsion of the target on the core alone is then sufficient to break up the halo projectile. There has been considerable debate among theorists about whether or not, having broken up, the particles still attract each other sufficiently to form a ‘soft dipole’ excited state or resonance at low energies in the breakup continuum.

All these features are most clearly seen for the last two neutrons in  ${}^6\text{He}$  and  ${}^{11}\text{Li}$  [5], and for the last neutron in  ${}^{11}\text{Be}$ . They are accentuated when the halo nucleons can occupy  $s$ -states relative to the central core. We have recently investigated  ${}^{14}\text{Be}$ , where possible low-lying  $s$ -wave states in  ${}^{13}\text{Be}$  contribute distinctively [6], and also studied [7] the proton drip-line nucleus  ${}^{17}\text{Ne}$  in a model of  ${}^{15}\text{O}$  plus two protons.

In the three-body cases (all except  $^{11}\text{Be}$ ) there are two nucleons outside a core, bound in such a way that if one of the bodies is removed, the other pair no longer forms a bound state. This we call the ‘Borromean’ configuration after the Borromean rings of tradition and knot theory. This configuration means that at least three-body correlations must be treated explicitly. We find that three-body models [5] are much more successful than models in which the nucleons move independently in a mean field. In three body theories, the bound and continuum states can be treated with proper consideration of the transition at threshold.

### Current Uncertainties

Even taking into account the above experiments, a number of uncertainties remain concerning the detailed structure of halo nuclei:

1. The admixture of intruder levels in the ground state of two-nucleon halo nuclei is often difficult to precisely determine, because usually the core + one-nucleon system is unbound (the Borromean configuration).
2. The details of the pairing correlations are not always clear. Three-body models have tended to use either free nucleon-nucleon potentials, but density-dependent effective interactions appropriate to nuclear matter have also been used.
3. The ‘core’ in  $^6\text{He}$  is the  $\alpha$ -particle, which is relatively inert, but still the binding energy of  $^6\text{He}$  has important contributions from  $t + t$  degrees of freedom [8, 9]. The cores in the heavier halo nuclei are softer [10], but it is not clear to what extent they are excited by the halo nucleons.
4. In any reaction of a halo nucleus, excited halo states will typically be produced. Since, however, halo nuclei typically have only one bound state, all excited states are in the continuum. The physical role of continuum intermediate and final states needs to be clarified, especially the role of the two-nucleon continuum.
5. The calculation of E1 dipole breakup of two-neutron halo nuclei requires the calculation of the continuum states of the three-body  $n+n+\text{core}$  system. Because of the large size of the ground state, the wavefunctions in the continuum region  $0 < E < 3$  MeV must be accurately calculated, and it is precisely in this region that the existence of any soft-dipole mode must be examined. We find [11] that the scattering in this region is strongly influenced by the neutron-neutron correlation, but that it does not appear that this correlation is sufficiently strong to constitute a soft dipole resonance. Other continuum resonances are predicted by three-body continuum models, with a wide variety of structures.

## Low-energy reactions

When low-energy beams of halo nuclei become available, several new kinds of experiments become possible. In particular, reaction studies at incident energies near the Coulomb barrier. More precise elastic and inelastic angular distributions can be measured, along with fusion probabilities and transfer cross sections. Let us consider how such measurements may be used to resolve some of the uncertainties listed above.

### Halo elastic scattering

The elastic scattering angular distribution for energies around the Coulomb barrier is sensitive to the nuclear attraction at the surface, as well as to the depletion caused by any long-range excitation mechanisms. Halo nuclei have a more diffuse density, so even the Watanabe (folded) potential should have a diffuse real part [12]. There has already been a problem seen [13] in the forward-angle scattering of  $^{11}\text{Li}$  on  $^{12}\text{C}$  which may [14, 15] or may not [16] be related to this diffuseness.

Depletion at forward angles in elastic scattering is caused by any long-range reaction channels, so, for highly charged targets, there should be large effects of this kind [17] caused by the E1 couplings to and from low-lying breakup channels in the continuum. The elastic scattering cross section is reduced down to quite forward angles, because the E1 excitation mechanism is of such a long range. A similar depletion effect occurs in the dipole excitation of the first excited state of  $^{11}\text{Be}$  [18]. Of course this will only be seen if the 320 keV separation of the excited state can be resolved experimentally. It would be of interest to confirm the procedure with  $^{11}\text{Be}$  scattering, and then to perform this experiment for the elastic scattering of  $^{11}\text{Li}$ , where different direct measurements of the E1 distribution [19, 20] produce disparate results.

### Fusion cross sections around the barrier

There has been considerable debate in the literature concerning the possible enhancement (and/or reduction) of fusion cross sections for halo nuclei at barrier and sub-barrier energies. It is well known that couplings to inelastic states lead to a reduction in the effective barrier, and an enhancement of the fusion cross section. Some theoretical work [21, 22, 23] holds that similar considerations apply during the barrier traversal of halo nuclei, whereas others [24, 25] come to another conclusion. The latter believe that the large probability of breakup to the dipole channels (mentioned in the previous paragraph) depletes the elastic channel, and reduces fusion.

To date, the experimental evidence is unclear. Measurements [26] of the fusion of  $^{11}\text{Be}$  on  $^{238}\text{U}$ , are of insufficient accuracy to determine whether there is a barrier enhancement. RIKEN experimenters [27] have attempted to determine  $^9\text{Li}$  and  $^{11}\text{Li}$  fusion on a  $^{28}\text{Si}$  target, and found similar fusion probabilities for the two projectiles. Recently, fusion cross sections for  $^{6,7}\text{Li} + ^9\text{Be}$  and for  $^{6,7}\text{Li} + ^{12}\text{C}$  have been systematically measured and analysed to look for the dependence on the

relevant separation energies [28]. They found reductions of fusion up to 40%, for energies from near the barrier to approximately twice the barrier.

The modelling of the doorway processes leading to the fusion of halo nuclei is a non-trivial problem. The various models used [21, 22, 23, 28] make different assumptions about the lifetime of the excited states produced when the halo nucleons are perturbed in the reaction. These states are breakup states, it should be noted, and demand, ideally at least, a three-body model which takes elastic scattering, breakup and fusion processes into account in a unified manner. Such a model would describe the role of intermediate continuum states, even when these states are non-resonant, and do not even have well-defined decay widths. Such a model would moreover describe the reversible (virtual) production of excited states at lower energies (in the Born-Oppenheimer limit, these states would be produced *completely* reversibly), the irreversible (real) breakup at higher beam energies, and the smooth transition between these limits at energies of interest. Unfortunately, such a model is not yet available; the best we have are coupled-reaction-channels models [29] which discretise the continuum in a CDCC manner. These CDCC models, however, only include some of the continuum outgoing channels (when the projectile c.m. leaves the target, not when the fragments leave individually).

The fusion of two-nucleon halo nuclei such as  $^6\text{He}$  and  $^{11}\text{Li}$  would furthermore demand a *four*-body reaction model. We have four-body models for high-energy reactions [30], but these make the other (sudden) adiabatic approximation. A theory of low-energy reactions of halo nuclei would have to take into account the details of pairing in the initial and final states, as well as the mechanisms of both simultaneous and sequential pair transfers. These mechanisms have not been properly resolved even for ‘normal’ nuclei, and are complicated for Borromean halo nuclei by the lack of discrete intermediate channels during sequential transfers.

### Transfer reactions

We have previously studied the phenomenon of *s*-wave intruder orbits in the structure of  $^{11}\text{Li}$  [31], the best-known halo nucleus. Recently we have developed similar models for the  $^{12}\text{Be}$  and  $^{14}\text{Be}$  isotopes [6]. Although  $^{11}\text{Be}$  has a predominantly *s*-wave ground state, a three-body model of two neutrons plus an *inert*  $^{10}\text{Be}$  core can only reproduce the properties of  $^{12}\text{Be}$  if the valence neutrons occupy mainly the  $(p_{1/2})^2$  configuration with about 25% admixture of  $(sd)^2$  configurations [6].

Core excitation can also be included [10] when solving the  $^{12}\text{Be}$  three body problem since it has a large contribution to the g.s. of the subsystem  $^{11}\text{Be}$  [32]. Including the  $2^+$  first excited state of  $^{10}\text{Be}$  in the calculation, we find [10] that a significant part of the  $^{12}\text{Be}$  g.s. wave function has core excited components ( $\sim 40\%$ ) and that the valence neutrons are mainly in  $(sd)^2$  configurations with only 10% of  $(p_{1/2})^2$ . The neutron transfer reaction ( $^{12}\text{Be}, ^{11}\text{Be}$ ) would [10] discriminate between the inert-core and core-coupled models, even if the discrete states in  $^{11}\text{Be}$  cannot be separately resolved. Proton targets could be used for the (p,d) neutron transfer, enabling us to extract spectroscopic information without structure ambiguities associated with the light particle vertex.

### Inelastic cross sections

The measurement of the cross sections for stripping to core-excited states will also help to resolve some of the differences between the models for  $^{12}\text{Be}$  discussed above. It will be possible to determine, for example, the fraction of core excitation within the  $^{12}\text{Be}$  ground state.

The models of  $^{12}\text{Be}$  also differ in their B(E2) transition matrix elements between the ground state and the first  $2^+$  excited state. At high energies, however, the Coulomb B(E2) value cannot be unambiguously determined by experimental  $2^+$  angular distributions because of extensive Coulomb-nuclear interference effects. At lower energies nearer the barrier, a cleaner measurement should be possible.

### Summary

The ability to perform experiments with low-energy halo nuclei, to look at elastic scattering and individual reaction channels, will lead to a new range of tools for investigating their single-particle and particle-pair spectroscopic structures. For some reactions, such as transfers, existing reaction theories can be used to obtain accurate results; for other reactions, such as pair transfers and fusion, more complete reaction models still await development and application.

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